The Path to Affordable Long Term Failure Warning: The XRF-Wear Monitor

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Abstract: Long term early warning of wear related failure has recently been demonstrated for operational turbine engines. Particles recovered from Navy F/A-18 engine oil filters were analyzed for chemical elemental content using X-ray fluorescence analysis (XRF). [1] The data were compared with known engine metallurgy to determine the source of particles generated by wear, corrosion, and contamination. The identified sources agreed with engine history as recorded in the maintenance database. Normally operating engines showed low levels of wear particulates, as expected. The XRF filter debris analysis method (XRF-FDA) successfully identified every oil wetted wear-related failure as having elevated quantities of metals. Warning times in excess of 100 operating hours [2] were achieved through the ability of XRF to measure elements other than iron. Some engines undergoing high time replacements showed high levels of metals as expected; the method enables the low wear engines to be identified. These striking results have implications for planning of operations and maintenance. This paper presents the XRF-Wear concept for autonomous on-line monitoring of aviation engines and other high value machinery. An economically advantageous approach to assembling the wear-profile database of previously unmonitored equipment is offered in the context of a fully automated, field deployable, on-site expert system.

Keywords: wear, debris, particle, filter, wear source, corrosion, warning, X ray, XRF, fluorescence

Introduction: Wear related failures of high-value combat systems may be avoided through a knowledge of the wear condition of the individual weapon system. For numerous weapon platforms with advanced fine (3 micrometer) filtration, there are effectively no remaining wear-metal particulates for traditional spectroscopic oil analysis to detect, and maintenance becomes schedule-based rather than condition-based. [3]

Recent advances in machinery monitoring technology, discussed in this paper, have demonstrated the ability to forecast wear-related failures over 100 operating hours in advance for the F404 engine in F/A-18 aircraft. The method involves removing suspended particles from the circulating oil and analyzing their constituent chemical elements by X-ray fluorescence (XRF). Before proceeding to a discussion of the XRF monitoring method used in this study, we will briefly discuss the physical basis for the method, and related work by others.

The X-Ray Fluorescence Method: When an individual atom is missing an electron from an electron orbit, one of the electrons in an orbit further from the nucleus may fall into the vacancy and release its excess energy as a photon. The energy difference between the two electron orbits goes into the emitted photon. For inner shell orbits, the energy difference is large, and the emitted photon is a penetrating X ray. The exact amount of energy given to the photon is characteristic of the emitting atom. X-ray detectors can measure the photon energy, the value of which serves as a fingerprint of the emitting atom. Thus, a spectral measurement of the number of photons at each energy leads to a determination of which chemical elements are in the sample and in what quantities. Characteristic X rays may be produced in various ways, e.g. by electrons bombarding the metal target of an X-ray tube. The non-destructive X-ray analysis performed in the scanning electron microscope (SEM), performed for example in conjunction with ferrographic analysis, also uses these same characteristic X rays produced by electron bombardment. The characteristic X rays are called fluorescent X rays when the atomic vacancies are generated by incoming "primary" X rays, for example those emitted by an X-ray tube. Fluorescence refers to immediate photon emission in response to an absorbed incoming photon.

In the basic physical emission process, XRF spectroscopy is conceptually parallel to the well known atomic emission spectroscopy (AES). Of course, they differ in the way in which the electron vacancies are produced, but both involve electron transitions between bound orbits. For XRF, these transitions are between inner shells close to the nucleus, whereas for AES the transitions are between outer shells. This basic distinction leads to significant differences in technology and capability. The two methods are compared in Table I. Both methods can analyze all the essential structural metals whether produced by wear or by corrosion, as well as silicon (dirt), and are not limited to magnetic materials.

XRF is capable of measuring fine particles as well as plate metal samples. However, it is limited by the depth from which the X rays are capable of exiting the sample. Thus, a plate metal sample which is half an inch thick will give the same readings as a thicker sample of identical composition. This leads to a particle size effect, despite which XRF still produces large signals for large particles and small signals for small particles. The sensitivity to small particles, where X-ray absorption is negligible, is enhanced relative to thick samples. Compared to the well known particle size limitations of AES, which prevents measurements on particles larger than ~10 micrometers in size, [4] the XRF particle size effect is rather mild. Thus, the XRF method measures particles of all sizes.

XRF is a very sensitive technique. XRF can readily measure and identify the small amount of elemental metal in several atomic layers of an area one centimeter square. [5] This is a small thickness even when compared with normal machining tolerances of individual components.

TABLE I	OPTICAL	X-RAY
Spectroscopy:	AES, AAS	XRF, SEM-EDX
Orbital Electrons:	Outer Shell	Inner Shell
Photon Energy:	~1 eV	~1000-100,000 eV
Elemental ID:	Characteristic Lines	Characteristic Lines
Compositional Effects:	Interelement or Matrix Effect	Matrix Effect
Calibration:	Fluid standards (Relative)	Calculational or solid standards (Absolute or Relative)
Sample:	Fluid, fine ($\leq$10 μm) particle suspension	Fluid, solid, suspension (any size)
Science:	Mature	Mature
Technology:	COTS, lab, field	COTS, lab, field, On-line process monitoring

The capability to quantitatively determine the elemental content of the sample from X-ray fluorescence (XRF) measurements was developed at the Naval Research Laboratory and put into the public domain in the 1960s and 1970s. [6] NRL produced the first XRF spectrometer with electronic detection, multichannel analysis of energy dispersive XRF detectors, and public domain software for quantitative analysis, a combination whose legacy endures in today's commercial XRF instrumentation. The NRLXRF computer program incorporated fundamental parameters as well as empirical coefficient methods and treatment of particle size effects into one cohesive and flexible package.

Earlier XRF Work on Wear Particles: The utility of XRF for analyzing metallic content in organic fluids has been recognized for a long time, [7] and has become the basis of the fingerprinting of oil sources, the on-line process control of fuel oils for sulphur content, and the commercial availability of instrumentation for such purposes. In addition to its use on organometallics and dissolved metals, XRF has been applied to suspended metal particulates in oil lubrication systems. [8] On-line XRF monitors have been developed with the goal of sensing Fe concentrations in the parts per million range necessary for condition monitoring of turbine engines; [9] the instrumentation then available was found unsuitable for use on an operating engine. Several reports demonstrate the superiority of XRF over atomic spectroscopy for detecting failure modes involving large particles. In one specific case, a failure went undetected by properly performed atomic spectroscopy, but would have been detected in advance had XRF been used, as verified subsequently from the archived oil samples; in this study, XRF agreed closely with more laborious but highly reliable wet chemical analysis methods. [10] A study of Sea King helicopter engines was carried out on suspended particulates in drawn oil samples by Veinot, who concluded that XRF warned of an oncoming failure one sampling period (~15 operating hours) earlier than atomic spectroscopy. [11] Note that even when the particulates remain in the oil, XRF can offer improved warning time.

Other workers have made use of drawn oil samples of a few milliliters, from which they filtered the particulates for presentation to an XRF instrument. By removing the oil from the particulate sample, both the X-ray scattering and the X-ray absorption by the oil are avoided, the sample is concentrated, and metal detection limits are improved. While Fe and higher atomic numbers can be analyzed suspended in the oil, light elements like Mg, Al, and Si require the oil to be

removed. Meier, et al., [12] filtered drawn samples from a bearing on a test stand and performed XRF analysis on them: a pitted bearing produced little Fe (below 1 microgram/hour) during about 100 hours of operation without load, but the wear rate immediately increased 2 orders when the load was applied. This work demonstrates that the sensitivity of XRF is sufficient even to observe changes in operating conditions of a single bearing experiencing advanced wear.

These examples of XRF analysis of wear particulates all assume that the particulates are present in the circulating oil. The same assumption is made by the spectroscopic oil analysis program (SOAP) for monitoring the condition of major machinery in the DoD. For numerous modern machines with fine filtration, this assumption no longer holds: the particulates are essentially all collected in the system's canister oil filter. Fine filtration extends machine life, but removes the ability to ascertain the end of that life using SOAP or other methods relying on the presence of suspended particulates in drawn oil samples. At present, many such systems are maintained on a scheduled basis rather than by condition monitoring. However, by examining the particulates concentrated in the canister filter, considerable insight into the machine condition can be achieved.

The JOAP-TSC Study of F404 Filters, Procedure: The Joint Oil Analysis Technical Support Center (JOAP-TSC) conducted a study [1] of engine oil filters collected from the F404 engines of operational F/A-18 aircraft. Although the filter, when new, passes particles in the size range which SOAP can detect, it effectively becomes a fine filter in use as deposits accumulate and entrap particles as small as 3 micrometers or less. The filters were pulled by the mechanics at the normal interval of 200 operating hours. There was no requirement to collect multiple filters from individual engines. Each filter was assigned a reference number to enable tracking and sent to the JOAP-TSC for analysis. Particulates were recovered from each filter individually by immersing in a fluid bath and sonicating for 5 minutes. The released particles were collected on a membrane filter patch, fixed in place with a polymer, and presented to the XRF instrument, a commercially available Spectrace 6000. The XRF unit automatically pumps down to vacuum and carries out a measurement protocol to determine 18 pre-selected elements in the sample. (The elements were Al, Ag, Cd, Co, Cr, Cu, Fe, Mn, Mo, Ni, Pb, Si, Sn, Ta, Ti, V, W, and Zn.) The entire procedure is complete in 20 minutes for a single filter, which can be reduced to an average of 15 minutes per filter when processing several in succession. The values reported by the XRF analysis were entered into a database with a separate record for each of the 189 filters analyzed. The data for an individual element were analyzed and each was assigned an index value corresponding to a five level statistical ranking of the distribution for that element. Level 1 included data within one standard deviation from the mean; higher levels had successively larger quantities of the element. These results were then compared with the metallurgy of engine components. A decision tree was constructed by which the engine module containing the failed component would be called out. These wear source identifications were made at the module level, to enable comparison with the entries recorded by the mechanics in the Aircraft Engine Maintenance System (AEMS) database. The AEMS database includes information such as the time on the engine, serial numbers, which module was maintained and when, and whether the engine had experienced a failure or was operating normally. The identity of the individual failed part is generally not available.

The JOAP-TSC Study, Results:

Since wear particle monitors historically have functioned as critical failure warning devices, the results were examined for engines which had suffered a failure of oil-wetted parts. Filters from

corresponding filter showed elevated quantities of a major metal. In addition, the metals found in the filters were the metals to be expected from the module which had failed.

A detailed example will illustrate the utility of the method. Two oil filters were taken from engine serial number 310810. Oil filter number 1 was removed from the F18 engine at 2548 hours since new (HSN). XRF found Ti, Mo and V at Level 2, and Co at Level 3. The Ti and V indicate a Ti 6-4 alloy and the Co and Mo indicate tribaloy coating. This combination of elements, Ti, V, Co and Mo, can originate from the Fan and High Pressure Compressor (HPC) modules. When the second engine oil filter was removed 239 hours later (2787 HSN), Cd showed up at Level 2, V at Level 4, and Fe at Level 5. The Fe with V indicates abnormal bearing wear. This combination of metals, Fe, V and Cd , can originate from the HPC and also from the Low Pressure Turbine. Notice the radical change in the elements and their significance levels by the time the second sample was taken. Thirteen hours after the second filter was taken (2800 HSN), this engine experienced HPC failure. The elements in both samples indicated the HPC was a source of these elements. The XRF filter debris analysis technique indicated a problem 252 operating hours before the High Pressure Compressor failed. At 13 operating hours prior to the failure, the XRF technique indicated a bearing failure was in progress.

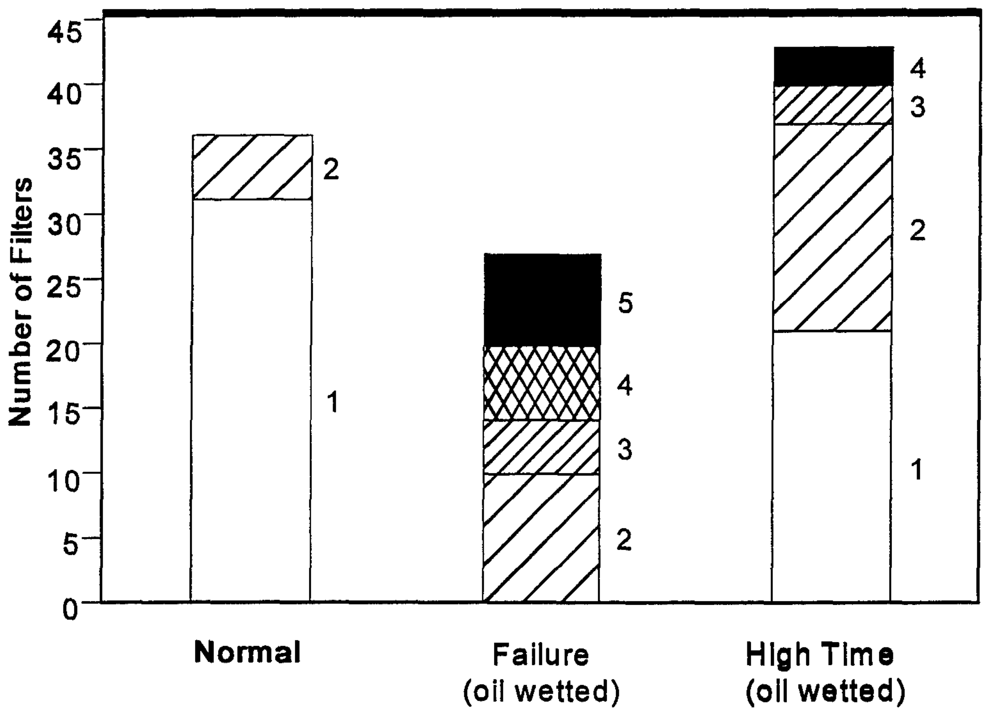

Figure 1. XRF analysis of filters for normal engines, failed engines, and engines at high time replacements. Increased levels of the three major metals (Fe, Ni, Ti) are assigned higher index values (indicated to the right of the bar). Most of the normal engines showed Level 1, while about 15% showed Level 2. None of the failed engines showed Level 1. High time engines clearly showed advanced wear in some cases (Levels 3 and 4), and low wear in others.

In addition to its long-term early warning capabilities, the XRF method can detect dirt contamination as well as corrosion and indicate where corrosion is occurring.

A wear monitor should also be able to correctly identify a normal engine, one which is not

experiencing abnormal wear. Approximately 85% of the normally operating engines (as so identified by the mechanics) exhibited metal levels within one standard deviation from the mean (Level 1) for the three major metals, as depicted in Fig. 1. The remaining normal engines had Level 2 for at least one of the major metals, but none showed any higher level. It is not known whether these Level 2 engines were entering into otherwise undiagnosed abnormal wear, but it is quite clear that the Level 1 engines were in fact in good wear condition, in agreement with the mechanics' assessments.

Figure 1 also reports the data recovered from engines which had undergone scheduled replacement of oil wetted parts due to the high amount of operating time they had experienced. In the absence of an effective condition monitoring technology, replacement schedules must be sufficiently conservative to prevent failures. The high-time data in Figure 1 clearly show that a significant fraction of the engines were in fact experiencing advanced wear, and were putting out Level 3 and Level 4 of the major metals. The schedule of replacements has been set to catch these engines prior to failure. However, the statistics of the process are such that nearly half of the replacements were for parts still operating at the low Level 1. That is, many of the replacements were carried out on normally operating parts. It is not known how much longer these normal engines would have continued with low levels of wear metal production; however, the availability of the XRF monitoring technology puts that finding within reach.

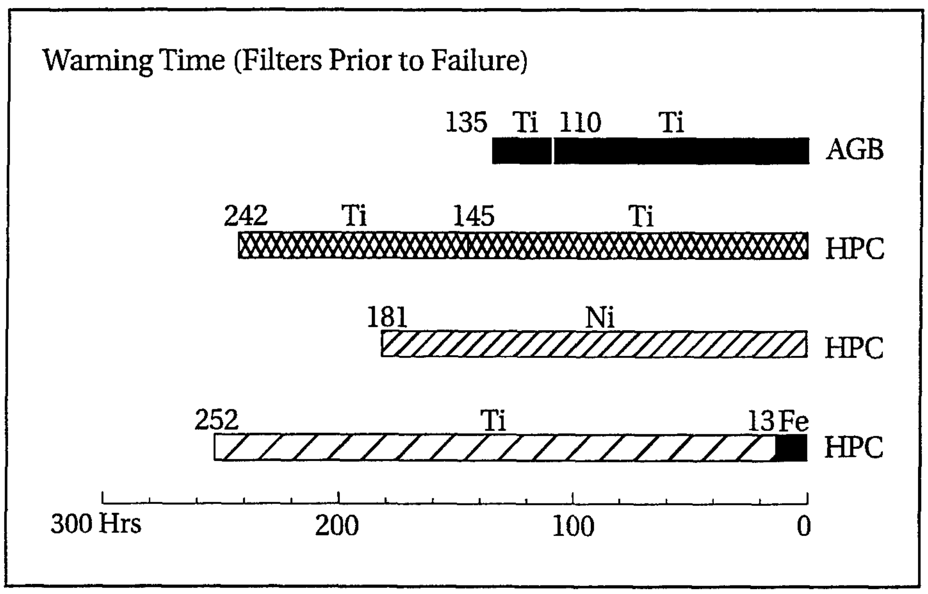

Figure 2. Filters pulled prior to failure showed long term early warning. The Levels are plotted with the same hatching as in Fig. 1. Numbers above the bars indicate hours prior to failure. Acronym (right) is the module which failed, also identified by XRF analysis. (AGB = Accessory Gear Box). High level metal is identified by chemical symbol.

Some filters were pulled because a failure had occurred. Others were pulled prior to a failure and showed high levels of wear metals. The data from these filters are presented in Fig. 2 as a function of time before failure. Note the remarkable time scale, extending out to hundreds of hours, well beyond the time scale of previous monitoring methods. In most cases, the high level metals were Ti or Ni. In other words, attainment of long-term early warning for the F404 is contingent upon elemental analysis of *nonferrous* alloys . Magnetic plugs or chip detectors would not have captured these alloys or indicated their presence. The XRF analysis also identified the engine

modules which later failed.

Management Implications: The implications of these capabilities for maintenance management are straightforward and important. [?] An individual machine which is unexpectedly nearing the end of its wear life can be identified and overhauled, whereas a machine which is unexpectedly *not* experiencing advanced wear can be left in service. This is the essence of condition based maintenance. The XRF method allows these decisions to be made on an individual machine basis, rather than on the basis of the statistics of a large number of machines. By insuring the timely repair of worn machines, secondary damage will be reduced. By extending the service of individual non-wearing machines, the average life of the population of monitored engines will be extended and the consumption of replacement parts reduced.

The availability of a long term failure warning technology also has implications for operations management. Here, it is important to identify the normally operating engines, and to commission these for deployment, thus avoiding the high cost of breakdown in remote locations or during mission critical operations.

The XRF-Wear Concept: The above benefits may be accrued by implementing the XRF-Wear concept for monitoring with a higher degree of automation than is currently available (see Table II). The XRF-Wear concept builds upon the three fundamental advantages of XRF filter debris analysis as a condition monitoring method: (1) the ability to measure particles of all sizes and alloy compositions, (2) the high sensitivity and wide dynamic range of XRF, and (3) collecting the sample from the full oil volume. The XRF-Wear concept is directed toward both on-site and on-line automated expert systems.

TABLE II **XRF-Wear Automation**	**Manual XRF** (today)	**XRF-Wear** (future)	
		On- Site	On- Line
Debris Collection			X
Debris Retrieval		X	X
Sample Prep/ Presentation		X	X
Sample Analysis	X	X	X
Action Limits/ Guidelines		X	X
Reporting		X	X
Multi- canister robot		(X)	

The on-line system will be able to monitor a single high value machine throughout its wear life, and automatically provide reports, maintenance warnings and condition assessment along the way. For use on board a manned ship or at a land facility with multiple machines, a design with a socket-mounted sensor head permits a single sensor to be manually moved from one machine to another as needed. For aviation, the system may be configured to issue an XRF-CBM squawk upon landing; in-flight warning could be provided, if required. Similar capabilities are envisioned for non-aviation applications. Remote operation with satellite links is one very real option; another is untended, autonomous operation for reduced manning situations on ship or shore.

The principal advantage of on-line monitors, namely the ability to protect a single vehicle or machine, is also its limitation. For the monitor to be able to issue warnings, it must have limits set for issuing those warnings. Setting the limits is an engineering function performed on the basis of

an accumulated database containing data on the wear profile of the engine type being monitored. Thus, accumulating the wear profile database becomes an essential prerequisite for effective monitoring. Using on-line monitors alone, that database can only be filled by accumulating the data produced by the monitors themselves. A statistically meaningful number of monitors must be installed on a statistically meaningful number of machines. During the initial period while the database is being established, the monitor cannot issue reliable warnings. Also, on-line monitors must be retrofitted onto each machine, or designed into a new system; either of these processes consumes calendar time.

A much more economical and immediate approach to accumulating the database is achieved with the on-site system. The process of collecting engine filters from a population of operational machines can begin immediately, even before the on-site system is either designed or built. Once built, the on-site system may be robotized to automatically process a rack of filters, without tending by an operator. The operator need only load a quantity of filters in the morning (each with its own identification or bar code), start the process, return at the end of the work shift to verify completion, unload the processed filters, and start another batch. Within a few days, an entire database can be accumulated for a new engine type which previously had not been monitored. Once the database is in hand, monitoring may proceed either with on-line monitors or by analyzing filters on-site.

The on-site system can also be supplied in a form suitable for smaller scale operations not requiring batch processing, in which individual filters are manually mounted and thereafter automatically processed. The throughput of such a system would still be substantial, since the operator is freed from tending the operation. This model of the on-site monitor is well suited to flight line, shipboard, laboratory, or installation usage. Using commercially available components, the system may be configured to automatically transmit the collected data to a central engineering database, to a management database, through an integrated local network such as the Integrated Condition Assessment System (ICAS), or to multiple destinations.

The on-site approach to filter debris analysis may be sufficient for many weapons platforms. With the long term early warning available with XRF-FDA, even a central filter analysis site (serving a large geographical area) may be effective in some cases. On-site filter debris analysis requires no retrofit, no additional poundage on board an aircraft, and no change in current practice other than to collect the filters. The on-site monitor may be used to analyze filters pulled at the normal cycles. In some cases, it may be cost effective to modify the filter changing period to insure sufficient warning time. Depending on the individual situation, this may be longer or shorter than the 200 hour period now in use with the F404 engine. For example, analyzing a filter just prior to a scheduled parts replacement may indicate or contraindicate the need for carrying out the replacement when initially scheduled. On the other hand, the occurrence of a chip detection event will almost certainly merit analysis of the filter debris; this analysis may be highly automated with the on-site monitor.

Implementing the XRF-Wear Concept: The state of current technology is ready for implementing the XRF-Wear concept. The power requirements of the system are modest. NRL has pioneered the application of computers to the analysis of X-ray fluorescence data, which now requires no more computational power than an Intel 80286 processor. XRF is miniaturizable. NRL has built an XRF system to fit within a 1.25 inch diameter pipe, and used it for environmental monitoring of subsurface soils. [13] The components in such a system employ technologies already present in flight systems. Automated filter debris recovery has been demonstrated with the Deployable Filter Debris Analyzer (DFDA) developed for the Canadian Department of National

Defence (DND) by GasTOPS Ltd. Individual filter canisters are mounted on the analyzer, and the particulates are then washed out, sized, and collected on filter patches. [14] The XRF-Wear concept may be implemented by extending the capabilities of the DFDA to include X-ray fluorescence analysis to achieve an on-site analysis station. Addition of rack mounting of filter canisters will enable the rapid accumulation of a wear profile database.

Summary: XRF-FDA is an effective technology for analyzing particulate contaminants in oil lubrication systems. The development of the XRF-Wear concept will enhance the ability of management to plan both maintenance and operations. XRF-Wear complements current trends toward fine filtration, longer life cycles, lower labor costs, and reduction of unnecessary replacements, while offering a path toward affordable readiness through condition based maintenance. The XRF debris analysis method is applicable to a wide variety of rotating and reciprocating machinery and fluids.

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